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THERMAL OVERLOAD PROTECTION

BACKGROUND OF THE INVENTION

[0001] The invention relates to thermal overload protection for protecting electrical devices, and particularly electric motors, from overheating.

[0002] Electric motors are utilized in several applications for driving various moving parts. An electric motor often has an associated control unit for adjusting and monitoring the operation of the electric motor, the speed of rotation, for example.

[0003] An electric motor may temporarily operate also overloaded, but if it becomes overheated as the loading continues, this may result in damage to the motor. Damage to the isolation of the stator coiling caused by overheating is the most critical.

[0004] Various solutions are known for protecting an electric motor against thermal overload. One known solution is based on 1..3-phase measurement of the motor current and on modelling the heating of the motor by using an RC equivalent circuit. The oldest and most common technical implementation is a bimetallic relay (thermal relay) coupled directly or via a current transformer to the main circuit.

[0005] A known solution is a thermal safety switch arranged inside or in connection with the motor, the switch tripping after a given temperature limit and interrupting the current flow through the electric motor. A more advanced version is an electronic unit that measures the temperature of the electric motor with temperature sensors and triggers a shut-off of the motor. This alternative manner is directly based on temperature detection with various sensors. The problem is the difficulty of placing the sensors correctly. Such a protection reacts relatively slowly.

[0006] In numerical protection, data is processed in a numeric format, i.e. digitally. Analogical measurement data are converted with an A/D converter into digital. The actual measurement and protection functions are implemented by means of a microprocessor. The thermal overload protection measures the root mean square (rms) values of the phase currents (load currents) of a motor or another object to be protected (e.g. a cable or a transformer), and calculates the temperature-dependent operating time. This thermal operating time may be accordant with standard IEC 60255-8:

$$t = \tau \ln \frac{I^2 - I_p^2}{I^2 - I_b^2}$$

wherein
t = operating time
τ = time constant
I_p = load current before overload
I = load current
I_b = operating current (maximum allowed continuous current)

[0007] The thermal time constant τ is determined as the time required of the object to be protected to reach a temperature θ, which is a given portion (e.g. 63%) of a steady-state temperature θ_s, when the object to be protected is supplied with constant current. The operating current I_p is the highest allowed continuous current, which also corresponds to the highest allowed temperature, i.e. the steady-state temperature θ_s. This highest allowed temperature is the trip level. Alternatively, the relative value of the thermal load on the object to be protected relative to a full (100%) thermal load can be calculated from the phase currents. The trip occurs when the relative thermal load reaches a 100% value.

[0008] Numeric thermal protection is thus associated with heavy calculation requiring an efficient processor and fast and expensive peripheral circuits, such as memories. Prior art solutions have employed an efficient processor having also an in-built mathematics processor, a floating point unit (FPU) or a corresponding unit for performing real-time calculation within a determined time. An efficient processor having library functions emulating a floating-point number unit has also been used. Implementations also exist wherein the algorithm is implemented with ASIC circuits, whereby they cannot be reprogrammed afterwards. Consequently, changes cannot be made to such a single-purpose circuit, but a new circuit is always required if the operation is to be changed. Implementations also exist wherein the current is measured/calculated, the warming-up is calculated, measurements are repeated etc., in a sequence. Such an implementation does not ensure fully real-time protection (no continuous measurement), but enables the use of a less efficient processor.

BRIEF DESCRIPTION OF THE INVENTION

[0009] The object of the invention is thus to provide a method for thermal protection of electrical devices and an apparatus for implementing the

method, allowing the calculation associated with the protection to be lightened and the technical requirements of the processors and peripheral circuits to be lowered. The object of the invention is achieved with a method and system that are characterized in what is stated in the independent claims. Preferred embodiments of the invention are described in the dependent claims.

[0010] In the invention, the time to tripping caused by thermal overload is also calculated in real-time if the operation of the motor is continued at the present load current. This information can be communicated to the operator, who is thus aware of the time available for any service or reparation work before the motor and a process possibly associated therewith are stopped.

[0011] In accordance with the invention, the mathematical equation or algorithm and its operands for calculating the time-to-trip are programmed suitable for an X-bit, preferably X=32, processor system employing fixed-point arithmetic in such a manner that a result or a provisional result never exceeds the X-bit value when the program is run in the processor system.

[0012] The current measured is preferably scaled into a unit value to a range of 0 to Y, wherein Y represents Y/100% of the nominal current, and preferably Y=65000, whereby the calculation is independent of the actual current range.

[0013] The invention enables calculation of the time-to-trip with a less efficient processor and less memory, which, in turn, lower the power consumption, production costs and physical size of the device. The calculation can be implemented with a simple and transferable code, which does not require a mathematics processor or mathematical libraries. However, the thermal load can be calculated with nearly the accuracy of a 64-bit floating-point number calculation, even if the processor used 32-bit fixed-point arithmetic.

BRIEF DESCRIPTION OF THE FIGURES

[0014] In the following, the invention will be described in more detail in connection with preferred embodiments with reference to the accompanying drawings, in which

Figure 1 is an exemplary block diagram illustrating the overload protection according to an embodiment of the invention,

Figure 2 is an exemplary signal diagram illustrating the operation of the device of Figure 1; and

Figure 3 is an exemplary flow diagram illustrating the operation of

the device of Figure 1.

DETAILED DESCRIPTION OF THE INVENTION

[0015] In Figure 1, a thermal overload protection is coupled between an electric motor M or other electrical device to be protected and a three-phase mains current supply L1, L2 and L3. S1 is a main mains switch, e.g. manually controlled, and S2 is a release switch controlled by the overload protection and controlled with a trip signal TRIP. The overload protection 1 measures the current load of each phase L1, L2 and L3 of the mains current supply of the motor M with a current measurement unit 10, which is based on current transformers, for example. In addition, the overload protection 1 may comprise a measuring unit 11 for measuring phase voltages. Further, the overload protection 1 preferably comprises a user interface, i.e. a human-machine-interface (HMI) 12, with a display 13 and a keyboard 14. Furthermore, the overload protection 1 may comprise a data communication unit 15 connected to a local area network (e.g. Ethernet), a bus (e.g. Profibus) or another data communication medium 17.

[0016] As regards the invention, the most essential function is related to the protection and control unit 16. The overload protection 1 is implemented with a microprocessor system, the majority of the above units being implemented with suitable microprocessor software and peripheral circuits, such as memory circuits. The measuring values provided by the current and voltage-measuring units are converted into numerical, i.e. digital values with digital/analog converters (A/D). In accordance with the basic principle of the invention, the microprocessor system employs fixed-point arithmetic, preferably 32-bit arithmetic. A suitable processor type is for instance a general-purpose processor having a 32-bit RISC instruction set, such as ARM7/9 or the M68k series.

[0017] It is to be appreciated that the above-described structure is only one example of a thermal overload protection for implementing the invention.

[0018] The overload protection 1 protects the motor M from overheating and from any damage caused thereby. The protection is based on calculating the thermal load on the motor on the basis of measured phase currents. In the following, the general operation of the protection will be explained by means of the example of Figures 2 and 3. Phase conductors L1, L2 and L3

are connected to the motor M by closing switches S1 and S2. The current-measuring unit 10 measures the currents of the phases (step 31, Figure 3), and the control unit 16 calculates the thermal load on the motor M on the basis of the phase currents by using fixed-point arithmetic (step 32).

[0019] Although the algorithm *per se*, employed for calculating the thermal load, is not essential to the invention, the following includes a description of a solution applicable to fixed-point arithmetic. The mathematical equation for one phase may be as follows:

$$\Theta_k = \Delta T * \frac{i^2}{C} + \left(1 - \frac{\Delta T}{R * C}\right) * \Theta_{k-1}$$

wherein

Θ = thermal load, preferably 0 to 200% preferably corresponding to a value range of 0 to 2.4

ΔT = interval for thermal load calculation, preferably in milliseconds

R = cooling factor of electrical device, preferably 1 to 10

C = trip-class factor

i = measured load current

[0020] Factor C is preferably a trip-class factor t_6, which indicates the longest starting time set on the motor relative to the actual starting time of the motor. Factor C may be for instance 1.7 (x actual starting time). In a primary embodiment of the invention, the trip-class factor t_6 is multiplied by a constant, preferably 29.5, or calculated by the formula $(1/k) * Te * (Ia/In)^2$, wherein Ia = starting current, In = nominal current, Te = allowed starting time, and k = constant. Constant k = 1.22 when an operating time graph corresponding to that of a combination of trip class and t_6-time is desired (operating times according to the requirements of IEC 60947-4-1). The measured current is preferably scaled into a unit value to a range of 0 to Y, wherein Y represents Y/100% of the nominal current, and preferably Y=65000, whereby the calculation is independent of the actual current range.

[0021] Let us examine 32-bit fixed-point arithmetic by way of example. The above-described mathematical equation or algorithm and its operands that calculate the thermal load are programmed suitable for a processor system employing 32-bit fixed-point arithmetic in such a manner that the result or the provisional result never exceed the 32-bit value when the program is run in the processor system.

[0022] The following is an example of a calculation equation structured and scaled in this manner

```
thRes =((ΔT*(i²/C)+ROUNDING)/MSEC)
+(((((MSEC*SCALING)-((ΔT*SCALING)/(R*C)))/SPART1)*th)/SPART2)
+thFract
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wherein the operand values are for example as follows

thRes = thermal load 0 to 200% corresponding to value range 0 to 24000

ROUNDING = e.g. 500

MSEC = e.g. 1000

SCALING = e.g. 10000

SPART1 = e.g. SCALING / 10

SPART2 = e.g. SCALING / 100

thFract = thRes of previous calculation divided by constant, e.g. constant = SCALING = 10000.

[0023] ROUNDING corresponds to decimal rounding. MSEC scales milliseconds into seconds. SCALING is accuracy scaling. The product of terms SPART1 and SPART2 represents the scaling of a time unit (preferably milliseconds), split into two parts to maintain calculation accuracy.

[0024] The result of the thermal load, thRes, is too high because of the scaling (in the example, within the range 0 to 24000), and it is scaled down to represent the thermal load per unit value employed, in the example to the range 0 to 2.4

Θ = thRES/10000

[0025] This quotient Θ is saved as parameter thFract and employed in the calculation the next time. Calculation accuracy on 0 to 100% thermal load is better than 0.1% of the thermal load.

[0026] The graph of Figure 2 represents the calculated thermal load Θ as a function of time t. When the motor M is started from cold state, it begins to warm up. In the same way, the calculated thermal load Θ increases as a function of time. When the thermal load Θ increases to a given set alarm level Alarm_level, the control unit 16 may give an alarm to the operator for instance via the user interface 12-14 or the communication unit 15 (steps 35 and 36 in Figure 3). The control unit 16 may also continuously or after a given level calculate the remaining time to trip (time-to-trip) and communicate it to the operator (steps 33 and 34 in Figure 3).

[0027] In accordance with the principles of the invention, the time-

to-trip τ is calculated by using a processor employing fixed-point integer arithmetic, preferably 32-bit. The mathematical equation employed as the basis of the calculation may be as follows:

$$\tau = R^*C^* \ln(a)$$

$$a = 1 - \left(\frac{\Theta_{trip} - \Theta}{i^2 - \Theta}\right)$$

wherein
Θ_{trip} = trip level for thermal load
Θ = calculated thermal load
τ = estimated time to moment when Θ reaches trip level Θ_{trip}
ΔT = interval for thermal load calculation
R = cooling factor of electrical device
C = trip-class t_6-factor
i = measured current

The equation and its operands are programmed into the microprocessor system structured such that a result or a provisional result never exceeds the 32-bit value.

[0028] In a preferred embodiment of the invention, the operators are as follows:

Θ = calculated thermal load 0 to 200% corresponding to value range 0-2.4
ΔT = interval for thermal load calculation in milliseconds
R = cooling factor of electrical device within range 1 to 10

C = trip-class t_6-factor multiplied by a constant, preferably 29.5, or calculated by the formula $(1/k) * Te * (Ia/In)^2$, wherein Ia = starting current, In = nominal current, Te = allowed starting time and k = constant. Constant k = 1.22 when an operating time graph corresponding to that of a combination of trip class and t_6-time is desired (operating times according to the requirements of IEC 60947-4-1).

[0029] The natural logarithm, ln(a) function, can be calculated either by using a small subset of the normal function or by using a look-up table. The selection between a small mathematical function and a look-up table is determined on the basis of the optimization need and the required deterministic level. This calculation is 100% deterministic when a look-up table is used.

[0030] The natural logarithm ln(a) can be written in the following

form:

ln(a).

$\ln(c) = \ln(e^{10}) + \ln(a) \Rightarrow$

$\ln(c) = 10 + \ln(a)$

[0031] As a result of this, in an embodiment of the invention, operator a and time-to-trip τ are calculated by scaled equations

```
a=1*e10_SCALING-(Θtrip -Θ)*e10_SCALING/(i2/PUCOMP-Θ))
τ=(R*C*(log(a)*SCALING-(LN_e10*SCALING)))/-SCALING
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wherein

Factor e10_SCALING (e.g. 22026) approximates scaling for e^{10} (e.g. 22026.47).

LN_e10 represents the function $\ln(e^{10})$. E.g. LN_e10 = 10 represents the function $\ln(e^{10})=10$.

i = measured current scaled into unit value, e.g. to the range 0 to 65000, corresponding to 0 to 650% of the nominal current,

SCALING is accuracy scaling whose value (e.g. 10000) depends on the required accuracy.

PUCOMP is per-unit compensation (e.g. 10000).

[0032] The estimation of the time-to-trip value τ can be calculated at a slower rate, for instance 10 times slower rate than the thermal load. However, τ should be calculated at least once a second. The accuracy of the result is better than +/- 1 second.

[0033] An example of a look-up table is presented in Table 1.

```
Uint32 logTab[] = {
 0,     55452, 62383, 66438, 69315, 71546, 73369, 74911, 76246, 77424, 78478,
 79431, 80301, 81101, 81842, 82532, 83178, 83784, 84355, 84896, 85409, 85897,
 86362, 86807, 87232, 87641, 88033, 88410, 88774, 89125, 89464, 89792, 90109,
 90417, 90715, 91005, 91287, 91561, 91828, 92087, 92341, 92587, 92828, 93064,
 93294, 93518, 93738, 93953, 94164, 94370, 94572, 94770, 94964, 95155, 95342,
 95525, 95705, 95882, 96056, 96227, 96395, 96561, 96723, 96883, 97041, 97196,
 97348, 97499, 97647, 97793, 97937, 98079, 98218, 98356, 98492, 98627, 98759,
 98890, 99019, 99146, 99272, 99396, 99519, 99640, 99760, 99878, 99995,100111,
100225,100338,100450,100560,100670,100778,100885,100991,101095,101199,101301,
};
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Table 1.

[0034] In the table, the value of operator a functions as the index in sequences of 256. If a<256, the first value of the table, i.e. 0, is retrieved. If a = 256, the second value of the table, i.e. 55452, is retrieved; when a=512, the third value of the table, i.e. 62383, is retrieved, etc. The table substitutes the calculation of function ln(a) and, in the exemplary case, also takes the SCAL-

ING factor into account.

[0035] When the thermal load Θ increases to a given set trip level Θ_{Trip} (preferably 100% of the heat load of the motor), the control unit 16 activates a trip signal TRIP that controls switch S2 to open, whereby the motor M is disconnected from the three-phase supply L1, L2 and L3 (steps 37 and 38 in Figure 3). If the remaining thermal capacity of the motor after the tripping is too low (e.g. less than 60%), the protection 1 may prevent a new restart until the motor is cooled to a given level (restart inhibit) or during a given time (steps 39 and 40 in Figure 3). For start-up, the signal TRIP is again connected inactive and the switch S2 is closed. In an embodiment, the operator may control the control unit 16 into an override state, wherein the Trip level is double (override Trip level).

[0036] It is obvious to a person skilled in the art that as technology advances, the basic idea of the invention can be implemented in a variety of ways. Consequently, the invention and its embodiments are not restricted to the above examples, but can vary within the scope of the claims.